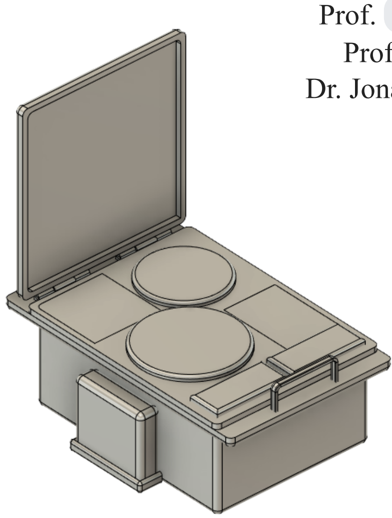
University of Michigan
Department of Aerospace Engineering

Project Title
LuVESS: Lunar Vacuum-Enabled Sample Solution

Design Team
Kaylee Bell (BSE Aerospace)
Karthik Bijoy (MSE Aerospace)
Christopher Clyne (BSE Aerospace)
Raquel Tejera Hernandez (MENG Aerospace)
Prachet Jain (BSE Aerospace + Engineering Physics)
Tara Vega (MSE Space Systems)
Sidharth Prasad (MSE Aerospace)
Kriti Rathi (MSE Aerospace)
Krishen Ratnayaka (BSE Aerospace)
Firuz Sharipov (BSE Aerospace)
Catalina Garza (MENG Space Engineering)
Anish Rajesh (MSE Aerospace)

Instructors
Prof. George Halow
Prof. Steve Battel
Dr. Jonathan Van Noord



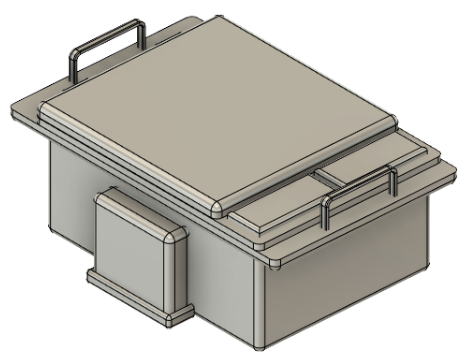


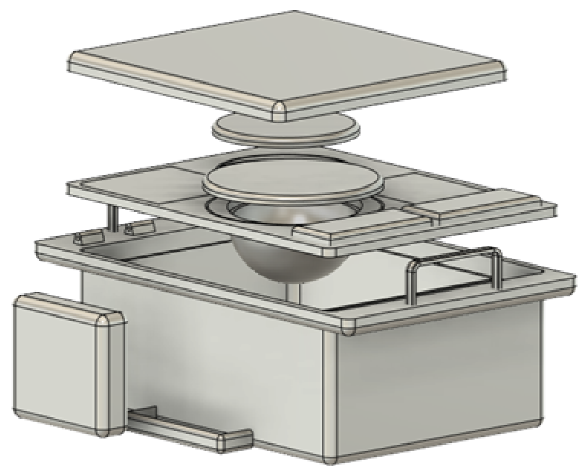
Table of Contents

University of Michigan
LuVESS: Lunar Vacuum-Enabled Sample Solution

Universal Sample Containment Theme

Objectives & Technical Approach:

- Expand understanding of solar system processes by enabling controlled storage and return of lunar samples to Earth
- Enable storage of biological samples in the same compact container
- Minimize power usage and heat loss after sample collection and return to Earth
- Maintain samples at collection temperature or colder, in ranges of 60-85K and 147-240K for lunar samples, and 277K for biological samples
- Enable sample collection at strategic points of interest on the lunar surface



Key Design Details & Innovations:

- Portable and lightweight briefcase design allows mobility on the lunar surface and maximizes available mass for samples.
- Lunar vacuum is harnessed and used as insulation for two cold storage containers to minimize heat loss and system mass
- Sun-shield lid ensures shading of samples and containers during collection.
- Power for cooling is not required on the lunar surface with insulation and sun-shielding.
- Eggshell shaped containers optimize thermodynamic transfer between samples and coolers.
- Cryogenic and thermoelectric coolers are used strategically to minimize power and overall system cost.

Schedule:

- Phase 1: Research and Development 2021-2022
- Phase 2: Validation and Testing 2023
- Phase 3: Critical Design Milestones 2023-2024
- Phase 4: Production 2024-Early 2025
- Phase 5: Artemis Launch and Deployment Mid 2025

Cost:

Materials	$386,250
Labor	$3,961,152
Facilities	$89,125
Margin	10%
Total	**$4,880,180**

1 - MISSION OVERVIEW

The Lunar Vacuum-Enabled Sample Solution (LuVESS) will expand our understanding of planetary processes, volatile cycles, the impact history of the Earth-Moon system, and provide a record of the ancient sun by enabling the transportation of samples [1]. LuVESS's two objectives will support Artemis Science Objectives and Activities by (1) storing samples for the return from the lunar surface and (2) preserving samples for study on Earth. To develop LuVESS, the team has imposed requirements for the system with the information given by RASC-AL, the Artemis Plan, and Exploration EVA System Concept of Operations.

On Artemis missions, we can expect a variety of scientific samples at temperatures ranging from +4 °C to -230 °C. Due to technological constraints, it is not possible to provide storage for the entire range. We instead selected intermediate temperatures that are likely to be encountered on Artemis missions. Temperature data from the Lunar Reconnaissance Orbiter and considerations for landing sites, specifically a plateau near Shackleton crater at 88.8 S and 125.5 E [1] were used to make determinations for the system's capabilities.

Artemis' science objectives have emphasized the need to collect geological samples, especially from permanently shaded regions (PSR). In our research efforts, we considered that astronauts can traverse 2 km on foot, 10 km by the unpressurized rover, and 12 km by the pressurized rover and analyzed the temperatures in each of these radii. Furthermore, only polar summer temperatures are of interest as missions are anticipated to take place during constant daylight. These radii and temperatures are depicted in Figure 1. While this effort helped us to deduce temperature ranges for non-PSR samples, no PSR fell within this range. Consequently, we identified other potential landing sites with similar illumination and slope then used the closest PSR to make an assessment. **As a result, the system shall be capable of storing PSR samples collected at a temperature between 60 K and 85 K and non-PSR samples between 147 K and 240 K. In addition to the geological samples, our system shall be capable of storing biological samples at 4°C from Artemis activities.**

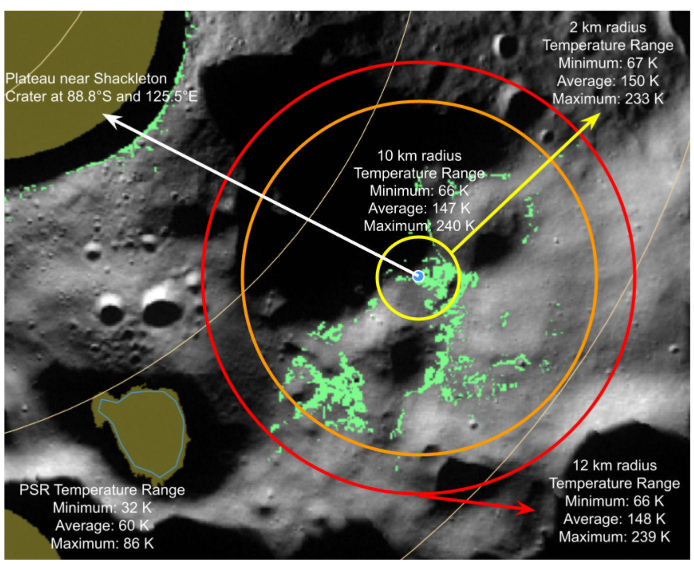


Figure 1: Radii and Temperatures near Shackleton Crater [20]

The second top-level requirement limits our system to 100 kg as mentioned in the theme. We have imposed an additional constraint stating that 35 kg of that total mass should be devoted to samples. This value was derived from Artemis Mission Plan.

The third top-level requirement ensures LuVESS will preserve samples from the point of collection to return to earth. This requirement is derived from the RASC-Al's second objective of preserving samples for return to Earth. The LuVESS system will have the capability to independently preserve the sample for 4 to 8 hours. In addition, LuVESS shall operate for 2 to 5 EVAs. This is the typical duration of an Artemis EVA as well as the typical number of EVAs conducted during a single Artemis mission. [1]. The LuVESS will have the capability to preserve the samples using external power from Orion, HLS, and gateway for 25 to 34 days. This is the typical duration of the Artemis mission [1].

The fourth top-level requirement demands LuVESS to be managed by the Artemis astronauts. This is to ensure that astronauts can monitor the sample health during transportation back to Earth. LuVESS will require transport by two astronauts as this is the minimum number of astronauts that will conduct an EVA.

The final top-level requirement for LuVESS is stated to exercise contamination control between samples to other samples, exterior, and internal environment. This requirement is stated to ensure the structural integrity of the LuVESS's systems during the entirety of the Artemis mission, including transportation between chains of vehicles. With this requirement, the pressure at which the samples are stored will be maintained for the entire duration of the mission. Finally, the LuVESS shall need to conform to planetary protection policy NID 8715.128 which is required to ensure that terrestrial biological contamination is controlled during and after EVA sessions.

2 - CONCEPT OF OPERATIONS

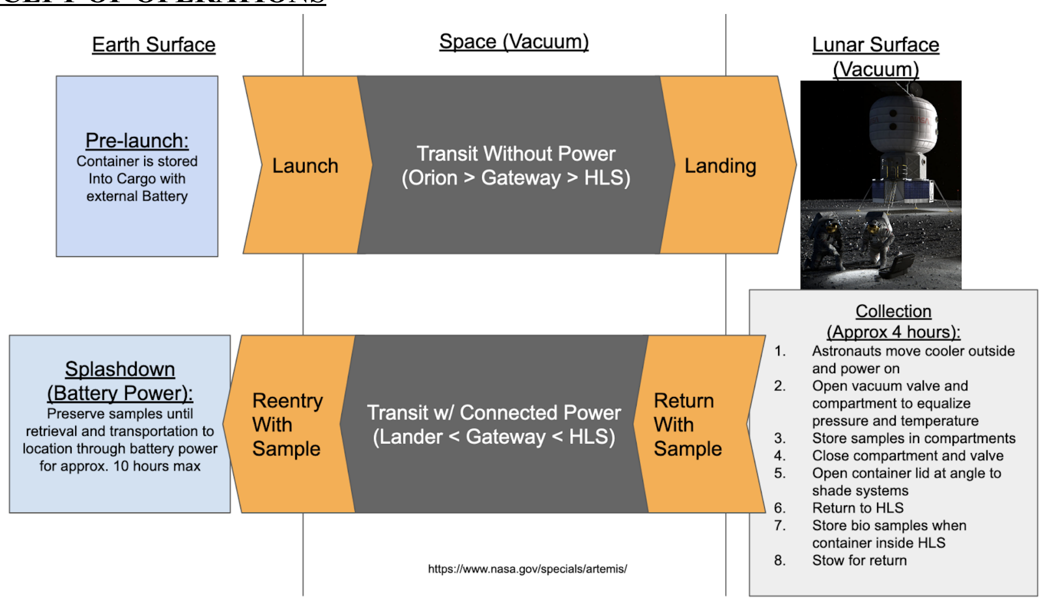


Figure 2: Concept of Operations Flow Chart

Before launch, the container shall be stored in the Orion storage, using the appropriate attachment system. The container shall withstand launch and transportation through the hatches of the Gateway and the HLS, being able to interface with storage on both spacecraft as well. Upon landing on the Lunar surface, the container shall remain inside the lander until time for collection of samples. The astronauts shall be able to lift the container without the side compartments designed for biological samples and take it outside for non-biological sample collection. The sensors and data collection hardware will operate on battery power for the duration of this phase, which is estimated to be up to 6 hours. On the lunar surface, they will open the vacuum valves to equalize compartment pressure and temperature with the collection area, and evacuate the insulation layer. The samples shall then be stored in the compartment, and the compartment shall subsequently be closed. The vacuum valves shall be closed and the container will have the lid propped up at an angle by astronauts. This will leave the radiators and other systems in the shade, increasing cooling. The astronaut will return to the HLS and connect the power for the container again. Biological samples are loaded into the container last through modular side compartments, which will be done while inside the HLS to minimize power draw from batteries and contamination. During the return trip, the container shall be transported back through Gateway and the lander, remaining on connected power. The container shall withstand splashdown and will remain on battery power until retrieval and delivery to NASA facilities, which is estimated to be approximately 4 hours.

3 - SUBSYSTEMS

3.1 - Structures

The structural integrity of the solution will play an essential part in deeming the project a success. The requirements that drive our design include **protection of the samples and critical components during launch, landing, and transport to the chain of vehicles**. The system must minimize heat losses and mass. We set a **target mass of less than 35 kg** for structures. Along with these requirements, we were required to be cognizant of the standards for NASA Extravehicular Activities (EVA), as having a solution that can be operated with ease and comfort is an equally important consideration. **The current design should be able to be carried by two astronauts, and they should be able to do so in their EVA suits with minimal bending over.**

3.1.1 - Structural Overview

The structural solution (henceforth referred to as the Briefcase) takes inspiration from the Apollo mission sample containment system, which had a similar briefcase configuration. Our briefcase is built of 3 layers, nested into one another.

The entire box is partitioned into two main sections: the sample containment section and the electronics bay, shown at the top of the next page The sample containment section holds Compartments 1 and 2 (C1 and C2). C1 and C2 are elliptical hemispherical compartments for holding lunar samples, one bigger than the other to allow different sizes of lunar regolith from Permanent Shaded Regions (PSR) and non-PSR. **C1 is connected to the cryocooler and will be dedicated for samples from PSR, while C2 will be cooled by thermoelectric coolers and is dedicated for samples from non-PSR.**

Both compartments have their dual lids sealed using **Astraseal O-rings** that are cryogenically stable [12], and also utilize the large main lid for protection. All the compartments utilize evacuation and insulation (Rohacell WF-200 PMI foam) [13] attached to the exterior to minimize heat losses.

The top plate acts as a direct interface between the astronauts and the box. Above the sample containment section, the samples will be put in the relevant compartment, and the temperature would be controlled from the control panels on the same layer. This section will be protected and sealed by the large lid.

Above the electronics bay, we have a heat sink to direct the thermal flow from the cryocooler, thermoelectric coolers, and batteries out of the system so that it will not interfere with the cooling of the system. We also have a control panel display that will be able to show real-time readings of the pressure and temperature inside C1, C2, and C3.

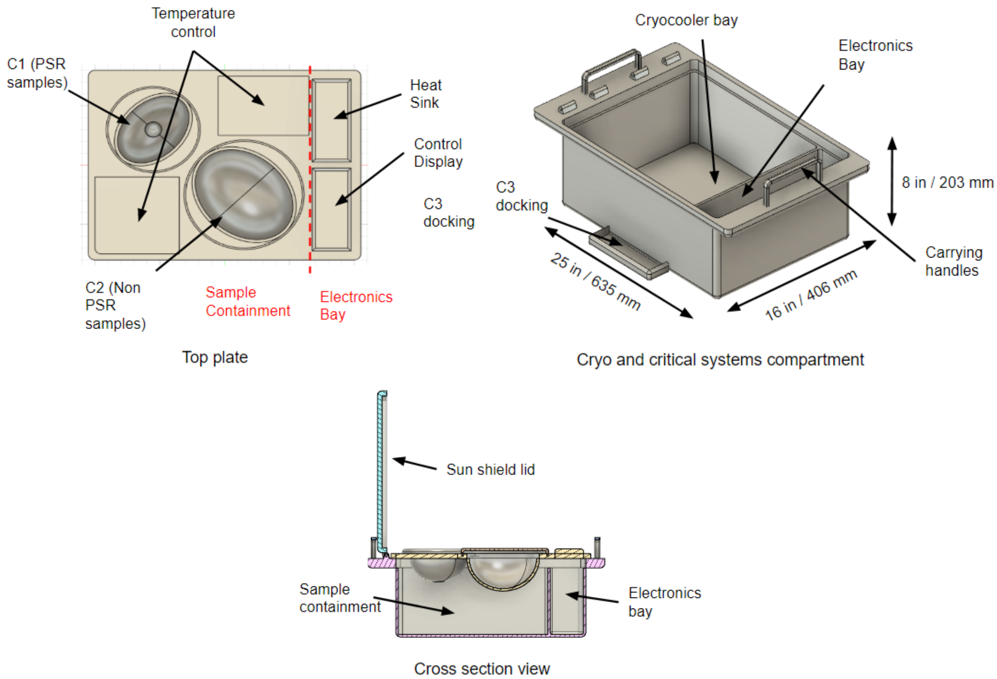


Figure 3: System Views

The second layer is the cryo and critical systems compartment, and this is where most of the systems dedicated to powering and keeping the system cool will be stored. This section acts as the outer protection of the entire briefcase and will be lined with insulation to prevent thermal losses. The handles are also attached to the system at this point, and this will be how the astronauts will mobilize the system. The bottom of this compartment also acts as the docking station for the **biological sample containment**, designated as Compartment 3 (C3). There are two C3s docked on either side of the briefcase and are connected through ports to the wiring inside of the cryo and critical systems compartment. The C3s are **not meant to be taken outside onto the lunar surface** for sample collection, as biological samples wouldn't need to be present on the surface of the moon. So, as included in the ConOps, we will be detaching this from the briefcase during sample collection, and the C3s will only be a part of the system during transport between the moon and the Earth.

Finally, the last critical system for the structures is the Main Lid. This lid will double as a **sun shield** to protect the briefcase along with the critical components during sample collection; the hinge design allows for it to stand up vertically with a 90° freedom of rotation. and acts as a redundancy measure for sealing, as well as helping with keeping the system structurally sound. The lid would likely be latched with a bolt system using the power tools the astronauts would have on hand during a mission, and this is being finalized.

3.1.2 - Materials

After careful evaluation of metals vs composites, we decided to stick to metals, specifically Aluminum alloys as they have a well-established design, procedures, rules, and design data. After detailed trade studies, we decided to go forward with **Aluminum 7075-T6**. Aluminum's high thermal conductivity and corrosion resistance make it useful for the production of heat sinks and heat exchangers, and its high strength and low density make it useful for the production of lightweight components for spacecraft, satellites, and lunar structures [6], and is graded for use in space applications. One thing we will have to take care of in our design is thermally protecting Aluminum from large changes in temperature to avoid strain.

3.1.3 - Sample Collection Method

As mentioned in the ConOps, the Astronauts shall be taking sample collection bags along with the briefcase to collect the samples and store them. In comparison to the Apollo missions, the additional requirements for preserving volatile samples alters the requisite materials needed for sample containment. Hence, we decided to use sample collection bags to minimize the probability of reaction between volatile compounds found in lunar regolith with aluminum of the briefcase. **These bags will be made of ECTFE, also known as Halar**®, instead of Teflon as previously used in Lunar missions. Products made out of ECTFE have excellent mechanical, electrical, and chemical properties and are often chosen for applications requiring excellent barrier-resistant properties [7]. We plan to use **5" x 5" bags** in our system.

3.1.4 - Insulation

To minimize heat leaks into storage tanks and transfer lines, high-performance materials are needed to provide high levels of thermal isolation. Complete knowledge of thermal insulation is a key part of enabling the development of efficient, low-maintenance cryogenic systems [8]. Thermal insulation systems provide energy conservation and allow system control for process systems. After a Careful review of studies conducted by NASA and other organizations such as the Cryogenic Society of America, we believe using Rohacell WF-200 PMI [13] foam would suit our requirements.

3.1.5 - Dust Mitigation Strategies

With the past experience of "The Dust Problem" in the Apollo Lunar missions, there is no doubt that incorporating dust mitigation strategies for sample preservation is essential. The jagged, electrostatically charged lunar dust particles can foul mechanisms and alter thermal properties. They tend to abrade textiles and scratch surfaces [9]. We intend to use the lid as a dust mitigation strategy, with an **electrostatic dust tarp** potentially attached underneath it. This could trap dust that would be present on the lunar surface during dust collection, however, this strategy would probably not be able to contend with large amounts of dust. Additionally, before opening the briefcase, **passive techniques like dust brushes can be used, along with active techniques such as electrostatic dust removal.**

3.2 - Cryogenics

The cryogenic system is responsible for introducing and maintaining the different temperatures required for storing and preserving the samples through the chain of vehicles during the mission. These compartments will be **capable of storing samples collected at temperatures between 277K and 43K** (4ºC and -230ºC).The sample stowage system will utilize a **sun-shield to reduce radiative heat transfer** from the Sun, while also being covered in white paint to reflect the Sun's rays. The main structure of the box will utilize **multi-layer insulation** all around the surface of the box to minimize heat gain from the ambient environment to the container.

In our design, there are three storage compartments differentiated by their temperature. Two of the storage compartments have an **elliptical hemispherical** (egg-shell type) shape. This particular shape was chosen to **minimize heat losses** due to sharp geometry. The storage compartments are placed inside the larger cuboidal structure of the box.

Both compartments, along with the cuboidal structure, will be **evacuated using aluminum tubes and manual ball valves**, which will be opened on the surface of the moon to vent any existing pressure, before being closed for the duration of the mission to prevent pressure build-up. Specialized spring-energized seals will be used to maintain the vacuum inside the compartments. Each storage chamber will also utilize Rohacell WF-200 foam insulation to minimize conductive heat transfer from the metal-on-metal contact surfaces, and will additionally be **gold-plated,** as gold's low emissivity minimizes radiative heat gain.

The third storage compartment acts as an add-on compartment to the main structure and is specifically designed to store biological samples. The separation of this compartment from the rest of the structure was **necessitated by the relatively high temperature of the biological samples** (compared to lunar samples), which would otherwise decrease the efficiency of the passive cooling process. Additionally, taking biological samples out on the surface of the moon was deemed counterproductive and potentially hazardous for the samples, so the compartments were separated. Biological samples can be stored in specialized biological freezers (MELFI/ Glacier) while the cold stowage solution is on the lunar surface, and they can then be added back to our sample container before re-entry procedures begin.
The chamber-specific design and functionality are discussed below.

3.2.1 - Compartment 1 (C1)

Compartment C1 will store samples at 85K, and the temperature of this compartment can be adjusted to as high as 150K by adjusting the cooler power draw. These samples will primarily be collected from Permanently Shaded Regions (PSRs). To accomplish this, the compartment will use a **Stirling Cryocooler,** specifically the **Sunpower CryoTel DS Mini**, which is capable of removing up to 2.5W of heat at 85K [2]. Through preliminary calculations (see Appendix 6.1), it is estimated that the total heat coming in through radiation will be on the order of 2W, and it is expected that this number will be reduced further once finite element analysis simulations are carried out to better quantify the heat transfer in our system. From a mass standpoint, the cryocooler weighs **1.8Kg**, which fits well within our mass budget. Cryocoolers are also simpler to use compared to other cooling solutions, and the absence of requiring a cooling fluid decreases risk within the system. The chosen cooler is expected to cost $250,000. C1 will also be supplemented by two thermoelectric coolers [3] to maintain a stable temperature on the surface of the moon, when use of the cryocooler may not be possible due to power constraints.

3.2.2 - Compartment 2 (C2)

Compartment C2 will store samples at 240K, primarily collected from non-PSR regions. To accomplish this, the compartment will use two thermoelectric coolers, specifically the **Laird RH14-32-06-L1-W4.5,** which is capable of inducing a ΔT of 60 K from an ambient temperature of 300K. This temperature change occurs by removing 2W of heat [3]. The heat needed to be removed due to radiation was calculated to be 1.7W (see Appendix 6.1). It is again expected that this number will be reduced with high-fidelity simulations. Thermoelectric coolers were chosen due to their flight heritage in some NASA applications [4]. They are simple to use and lightweight (on the order of 50 grams). They are expected to cost roughly $50 per cooler. The heat from the cryocooler and the thermoelectric coolers will be carried out to a radiative surface on the container through copper pipes.

3.2.3 - Compartment 3 (C3)

Compartment C3 will store samples between **277K and 253K**, based on the typical temperature of biological samples [5]. The compartment will utilize two of the same thermoelectric coolers as C2, with the difference being that the heat load on these coolers will be higher due to the relative lack of thermal protection and passive cooling.

3.3 - Power and Controls

The control system will monitor and adjust the temperatures of each compartment to ensure that the samples are stored at the desired settings. It will also monitor the pressure of C1 and C2 and the surrounding vacuum insulation to verify that each compartment is evacuated. It will notify the user of any errors, and record data for the duration of the mission.

3.3.1 - Control Panel

Through the control panel the astronauts would be able to check the status of the system and the samples and select the desired setup. It is placed on the top surface of the case for ease of access and readability. It is protected by the lid when not in use to avoid accidental changes. It is conformed by:

- **13 four-digit, seven-segment displays**, to show the current temperature and pressure of the compartments, the selected temperature, and the conditions of the electronics bay, battery, and heat sink
- **LED lights,** to indicate the status of the different compartments
- **3 continuous position rotary knobs,** to select the desired temperature
- **4 toggle switches,** to turn different parts of the system on and off depending on the stage of the mission

The type of switches and knobs, their sizing (5cm in diameter), as well as the distribution and location of the control panel were chosen according to the **3000 NASA standard**.

3.3.2 - Control System

The system is **closed-loop**. The microcontroller receives data from the control panel and the sensors, processes the information, and adjusts the different systems to obtain the selected set-up. Based on the sensor's readings, it detects errors in the system and notifies the astronauts through the control panel and/or alert system in the pressurized environment. All this information is continuously stored in the hard memory of the system, for reference about the storage conditions of the samples since their collection, and detection of system errors. In order to reduce power consumption during EVA, depending on the stage of the mission, the system would operate with only the required systems on.

The system will be configured with a **microcontroller (TBD)** and a **hard memory (Mercury RH3440 SSDR** [14]**),** which are located in the electronics bay. **Three pressure transducers (ST 1300 Series** [15]**)**, placed on each of the pressure valves, will measure the pressure of the compartments and check for leaks. **Three humidity sensors (TBD),** located in the electronics bay, monitor humidity around the electronics, which could cause condensation and system failures. There are **26 temperature sensors in all**, as follows: 18 **YSI 44000 Series 10K Thermistors** [16] will be used to measure temperatures down to 233 K and are placed around the electronics bay, battery, heat sink, C3, and C2. 6 **Honeywell 700 Series 1000 Ohm RTDs** [17] will be used to precisely measure temperatures down to 110 K and are used for the most critical parts of the system (battery, heat sink, and all sample compartments). Two **Lake Shore Thermal Diodes** [18], used for C1, precisely measure temperatures down to 45 K.

3.3.3 - Sensor Arrangement

The temperature sensors of C1 and C2 will be placed on the outer surface of the compartments' shells to prevent compromising the sample's vacuum. The sensors of C3 will be placed inside the compartment. These will be evenly distributed to ensure that the compartment is evenly cooled at the same temperature. The temperature sensors monitoring the electronic components would be placed around the electronics bay, following the heat flow of the system.

The selection of these components was based on thermal zone, complexity, system cost, and criticality trade. The number of sensors was based on thermal system design, specific application, criticality, and redundancy. The system design was based on the thermal model, need matrix, and practicality of measurement. The architecture of the design was determined by human and system safety, hardware safety, testing, sample management, and transport knowledge.

4 - RISK MITIGATION

Risk Management has been an important part of our design process. We applied Continuous Risk Management (CRM) practices and techniques to identify and mitigate risks throughout the design lifecycle. Our current risk matrix is shown in Figure 4.

The SYS-001 (System Risk #1) Risk revolves around obtaining components necessary for testing. The primary Structures risk (STR-006) pertains to the infiltration of lunar dust into our system. This could potentially cause mechanical failure. We're exploring design elements that could minimize the probability of infiltration. Controls risks (CRL-###) are associated with sensors reading incorrect data from the environment. We have already implemented additional sensors for redundancy and will look into control systems that could be used to predict and correct errors. As for cryogenics sub-system related risks (CRY-###), those primarily revolve around the loss of vacuum in the storage compartment and the failure of the storage bags.

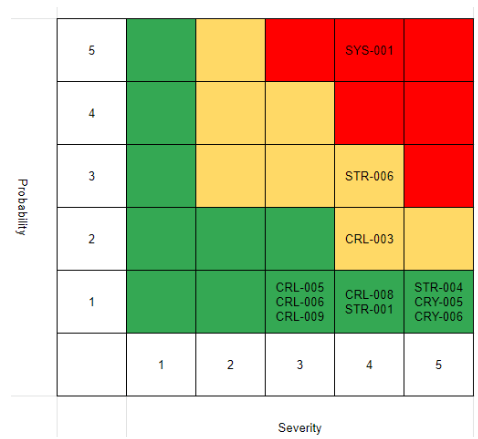


Figure 4: Current Risk Matrix

5 - TIMELINE & BUDGETS

Upon submission of this proposal, we plan to first set up and conduct heat transfer simulations through finite element analysis solvers. We then plan to purchase our specified thermoelectric coolers and conduct thermal testing using cryogenic vacuum chambers. These tests will help us verify our thermal modeling and estimations in an environment that closely resembles that of the lunar surface. Validation of our thermal modeling will allow us to proceed with building a prototype system for the competition.

Our current project cost is proposed below in Table 1. Labor costs are based on a combined total of 9 employees working 40 hours a week for two years. The individual labor costs are based on average salaries of personnel in the Climate and Space Science department at the University of Michigan. The facility costs are educated estimates made by the team. The timeline for the project is broken down in Table 2, targeting a mid-2025 launch date.

Technical power and mass budgets are proposed in Tables 3 and 4, respectively. Calculations for our batter capacity can be found in Appendix 6.3. With an assumed time of 15 hours for the battery, we calculate **1399.6 W-hrs**. Our current selection is the **EaglePicher NPD-002271** [19], as it has high specific energy and energy density values. A few other, more powerful options are being considered, but their mass and volume constraints may not be suitable for us. The required battery mass is about **9.12 kg** with 5.1644 L of volume.

Category	Item	Unit Cost	Quantity	Total Cost
Labor	Program Manager	$58/hour	2080	$120,640
	Systems Engineer	$58/hour	2080	$120,640
	Computer Engineer	$58/hour	2080	$120,640
	Integration Engineer	$40/hour	12480	$499,200
	Thermal Engineer	$40/hour	4160	$166,400
			Unloaded Subtotal	$1,027,520
	Fringe		30%	$308,256
	Overhead		60%	$616,512
	General and Administrative		40%	$411,008
			Subtotal	$2,363,296
Facilities	Workshop	$2,500/month	5	$12,500
	Clean Room [8]	$300/ft2	100	$30,000
	Testing	$1,000/day	15	$15,000
			Unloaded Subtotal	$57,500
	Overhead		55%	$31,625
			Subtotal	$89,125
Materials	Insulation	$1,900	–	$1,900
	Seals	$700	2	$1,400
	Sample Bags	$50	20	$1,000
	Thermocoolers	$50	6	$300
	Cryocooler	$250,000	1	$250,000.00
	7075Aluminum	$2,000	–	$2,000.00
	Electronics	$1,000	–	$1,000.00
			Unloaded Subtotal	$257,600
	Overhead		50%	$128,800
			Subtotal	$386,400
Total				$2,838,821
Contingency			10% of Total	$283,882
Grand Total				**$3,122,703**

Table 2: Project Timeline

Phase	Start-End	Duration
1: Research and Development	2021 - 2022	1.5 Years
2: Validation and Testing	2023	1 Year
3: Critical Design Milestones	2023 - 2024	1 Year
4: Production	2024 - 2025	6 Months
5: Launch and Operation	Mid 2025-	40 Days

Table 3 (left) and Table 4 (right): Power and Mass Budgets

System	Units	Volts	Amps	Max W	Power (W)
Cryocooler	1	-	-	-	45
Thermoelectric Cooler	6	3.9	5.9	12	72
Control System (TBD)	-	-	-	50	50 (est.)
7 segment LED display	11	3.4	0.02	-	0.748
Pressure sensor	2	5	0.02	-	7.02
Total					**174.768**

Mass Group	Current Estimate (kg)	Budget (kg)
Structures	34.6	40
Cryogenics	9.2	10
Electronics	3.0	5
Battery	9.1	10
Total	55.9	65
Mass of Samples	44.1	35

6 - APPENDIX

6.1 - Thermal Calculations

The primary thermal equation used in our thermal calculations was

(1) $$H = \epsilon \sigma A T^4$$

where:
H = Heat transferred
ϵ = Emissivity (chosen as 0.05 for gold)
σ = Stefan-Boltzmann's constant ($5.67*10^{-8}$ W/m^{2}K^4)
A = Outer surface area of storage chamber
T = Temperature
In order to quantify heat transfer between two planar surfaces, in this case between the outer chamber wall and the inner surface of the foam insulation, the following equation was used [21]:

(2) $$q_{net} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}$$

where:
q_{net} = Heat transfer/unit area
ϵ = Emissivity, subscript 1 or 2 denotes different values
For our calculations, we assumed an ambient temperature of 300K and a cold temperature of 85K. The outer surface area of compartment 1 was estimated to be 0.032 m^2, while the outer surface area of compartment 2 was estimated to be 0.059 m^2. Both these estimates came from CAD models.
For C1, the net heat into the compartment was calculated to be ~1.9W.
For C2, the net heat into the compartment was calculated to be ~1.7W.

6.2 - Dimensional Calculations

Looking at previous Lunar rock collection missions, the average diameter of rocks collected was 11cm and a mass of 0.3 kg per sample. Taking these assumptions into account and accounting for 35 kg of samples as the proposed sample collection mass in the Artemis mission con-ops.
This gives us an estimate that we would be collecting 117 rocks and using the assumption that their size could be spherically shaped with a diameter of 11 cm.
Comparing the total volume required to the volume of elliptical hemispherical compartments -

Volume = 2/3 * π * A * B * C = 117 * 4/3 * π * r^2

Where: A, B, and C are the lengths of all three semi-axes of the ellipsoid and C = A.

Gives us the dimensions of **A=C = 0.127 m** and **B = 0.178 m** for **C1**, and **A=C = 0.178 m** and **B = 0.229 m for C2**

6.3 - Battery Calculations

As seen in Table 3, by listing out all the major systems and their power draw, we get a maximum power draw of 174.768 W if all systems are simultaneously running in the worst case. Required W-hrs from the battery is calculated using the equation:

$$\text{Total capacity} = \frac{P_e T_e}{(DoD)(N)(n)},$$

where: Pe is the max power draw we calculated, Te is time on battery, DoD is the depth of discharge (assumed for 80%), N is the number of batteries (1 for now), and n is efficiency (assumed 0.9).

6.4 - Technological Readiness Level Summary

Name of the Component	TRL	Justification
AL 7075	9	Was used for the Zero fighter's airframe of the Imperial Japanese Navy in pre-war times.[11]
ECTFE sample collection bags	6	One of the products used in Non-Flammable Containment Bag and Enclosure Development for International Space Station Use study
Astraseal O rings	9	NES Astra Seal® has been successfully used in several space shuttle/rocket launches and a multitude of other demanding applications by organizations such as Boeing, NASA, and Lockheed.[12]
Rohacell WF-200 PMI foam	9	ROHACELL® WF is the core of choice for Boeing Space launch vehicle programs Delta II, III, and IV. [13]
CryoTel DS Mini Cryocooler	5	This cryocooler has undergone qualification testing but does not have flight heritage [10]
Laird Thermoelectric Cooler	7	Thermoelectric coolers have undergone prototype demonstrations in space environments [10]
MLI	7	MLI prototypes have undergone prototype demonstrations in space environments [10]
Mercury RH3440 SSDR	9	Flight proven solution for radiation intense environments [14]
7 segment LED display	9	Used in previous space missions.
ST 1300 Series Pressure transducer	8	Space rated component [15]
YSI 44000 Series 10K Thermistors	9	NASA has deemed YSI thermistors worthy of qualification for extended space flight [16]
Lake Shore Thermal Diodes	9	Lake Shore offers a rich history of working with scientists and engineers at a number of aerospace institutions and agencies, including NASA, supplying thermometry and other technology [18]
Honeywell 700 Series 1000 Ohm RTDs	5	Component has been validated in relevant environments [17]

6.5 - References

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